Propulsion & Power Technologies for The NASA Exploration Vision

A Research Perspective

Presentation to

Symposium on MHD Electrical Power Generation and Related Technology

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University of Tsukuba
Tsukuba Science City, Japan

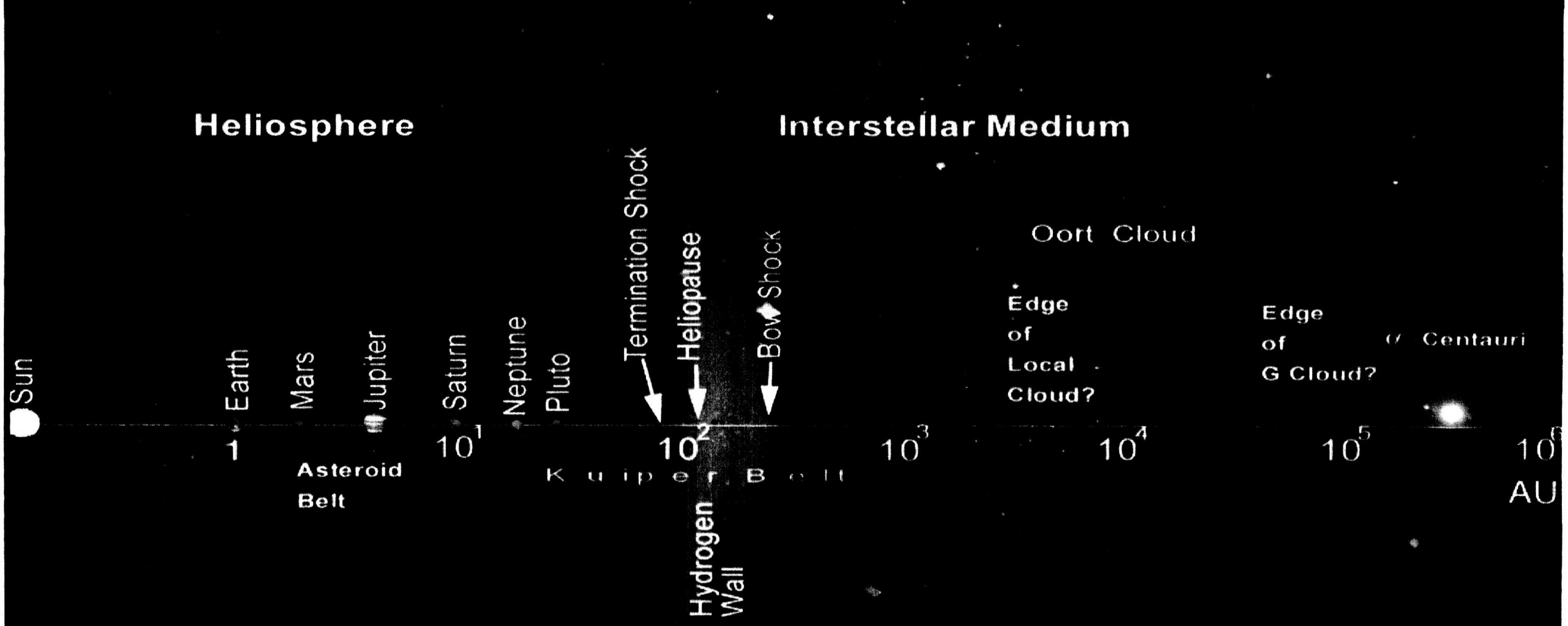
by

Ron J Litchford

Propulsion Research Laboratory
NASA Marshall Space Flight Center

The Challenge of Deep Space Expl

Distance & Time



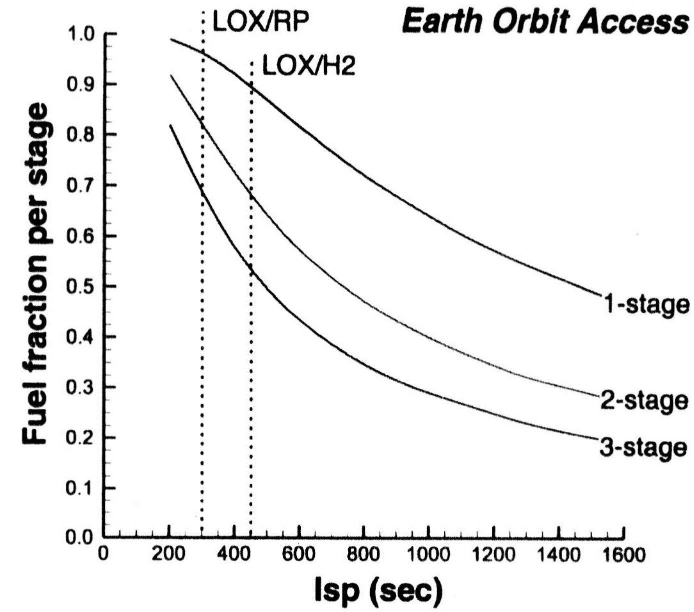
- Space transportation capabilities are currently limited by available propulsion & power systems
- Requirements for deep space exploration missions will require dramatic extensions in system energy & power densities

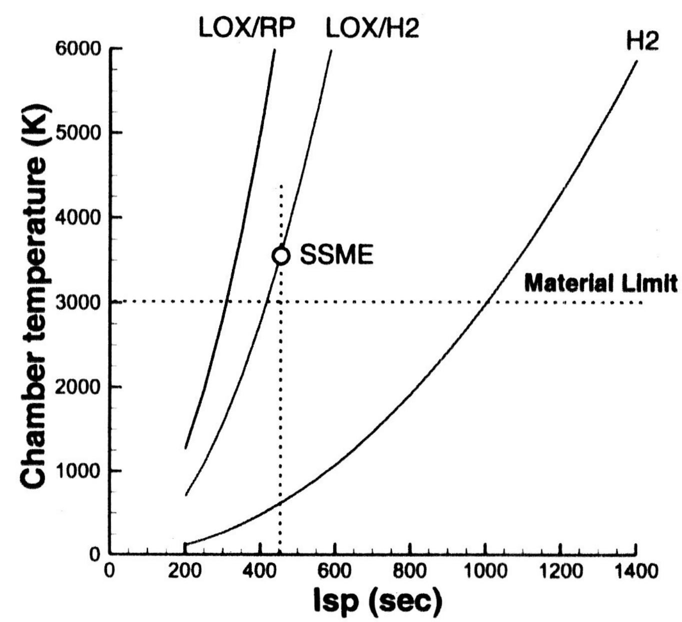
NASA / Interstellar Probe Science & Technology Definition Team

Technology Pull for Launch Tra

- ✦ **Increase payload by reducing fuel fraction**
  - Requires higher specific impulse (i.e., specific energy)
  - Chemical propulsion has limited specific energy
  - Need improved energetics in order to make revolutionary advances in propulsion capability
- ✦ **Thermal propulsion is constrained by material temperature limits**
  - Increased performance implies:
    - Higher chamber temperatures and/or decreased molecular weight
    - Increased component efficiencies and/or decreased inert dry weight
  - LOX/Hydrogen near thermal limits
    - Near maximum chemical energy density
    - Near minimum molecular weight
    - Pushing material temperature limits
  - Need innovative methods for bypassing thermal constraints
- ✦ **Promising avenues of research exist, such as**
  - Highly energetic fuels
  - New engine cycles
  - Electromagnetics/Beamed Energy

Earth Orbit Access

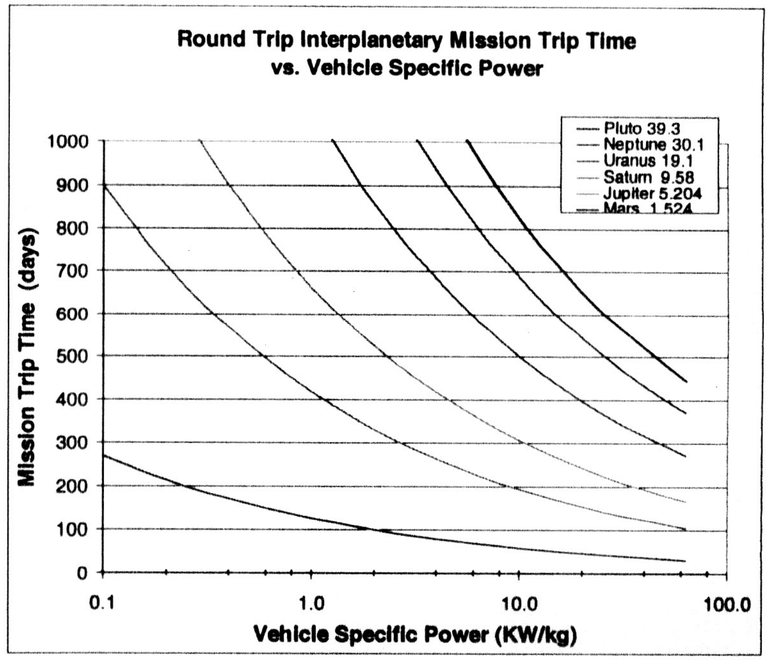




Technology Pull for Deep Space

✦ Deep Space Transportation Challenges

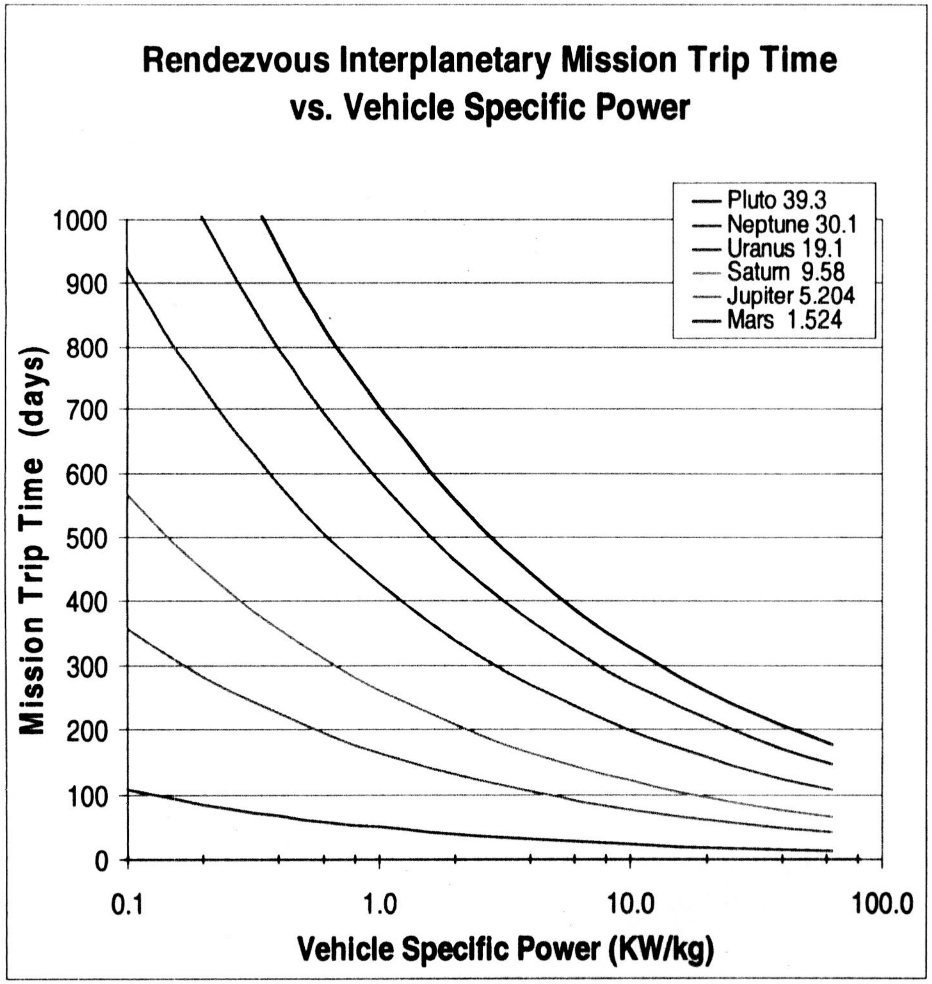
- The fundamental technical obstacles to deep space (mars and beyond) transportation are related to propulsion energetics
  - Specific Energy
    - low IMLEO demands high Isp propulsion
  - Specific Power
    - short trip times demand high Δv maneuvers (i.e., high jet power for high acceleration)
- Affordable, short-duration, on-demand travel to mars and beyond will require robust performance margins
  - Order of magnitude increase in specific energy
    - delivered mass fraction > 50%
  - Trip times measured in days rather than years
    - specific power > 1 kW/kg

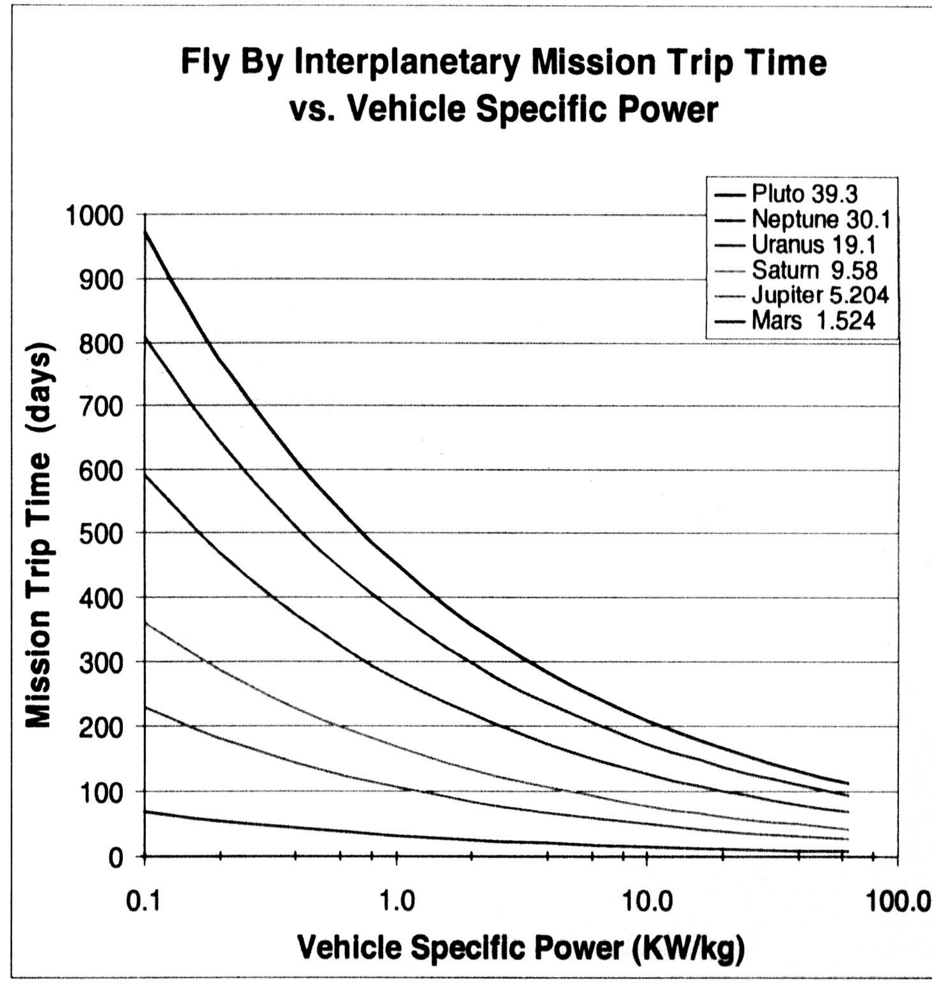


- Requirements far beyond current plans for Nuclear Electric Propulsion (~0.03 KW/kg)

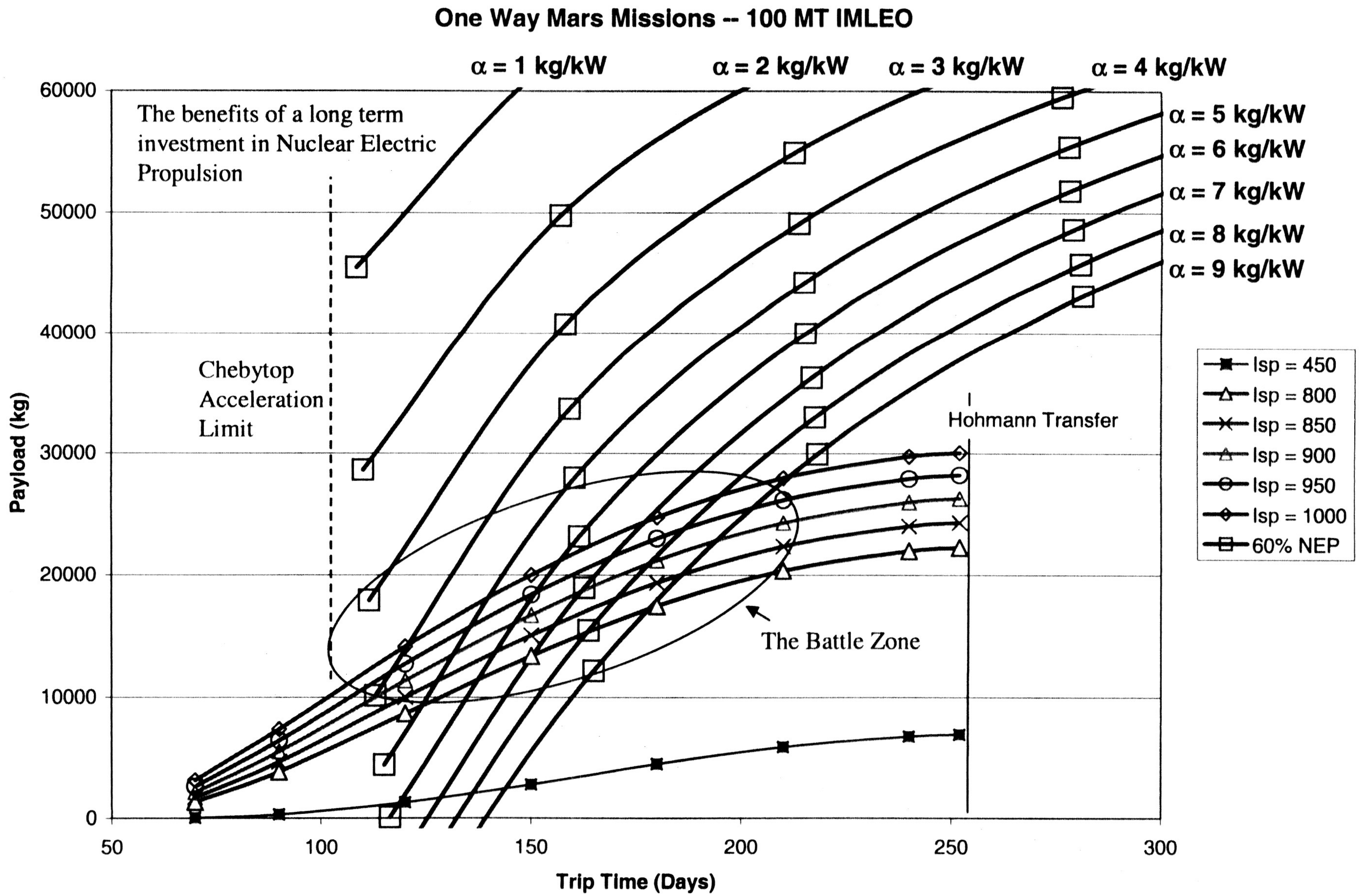
... need to break through 1 kW/kg barrier

Rendezvous and Fly-by Trip Time





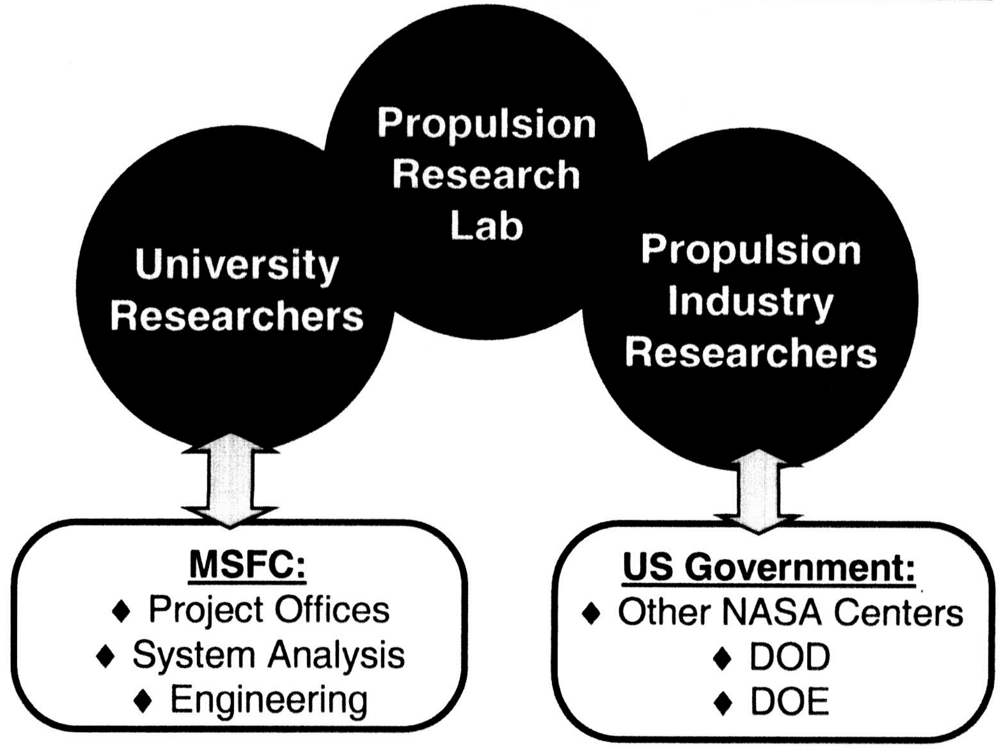
Nuclear Electric vs. Nuclear



MSFC Propulsion Research Lab

Disciplinary Branches

- **Chemical Propulsion**
  - high energy propellants
  - combustion physics
  - advanced engine cycles
- **Nuclear Propulsion**
  - simulated fission reactor systems
  - nuclear thermal propulsion
- **Electric & Plasma Propulsion**
  - high power thrusters
  - plasma containment / diagnostics
- **Energetics**
  - high energy/power density systems
  - spacecraft power conversion
  - aerothermodynamics & MHD
  - flightweight components

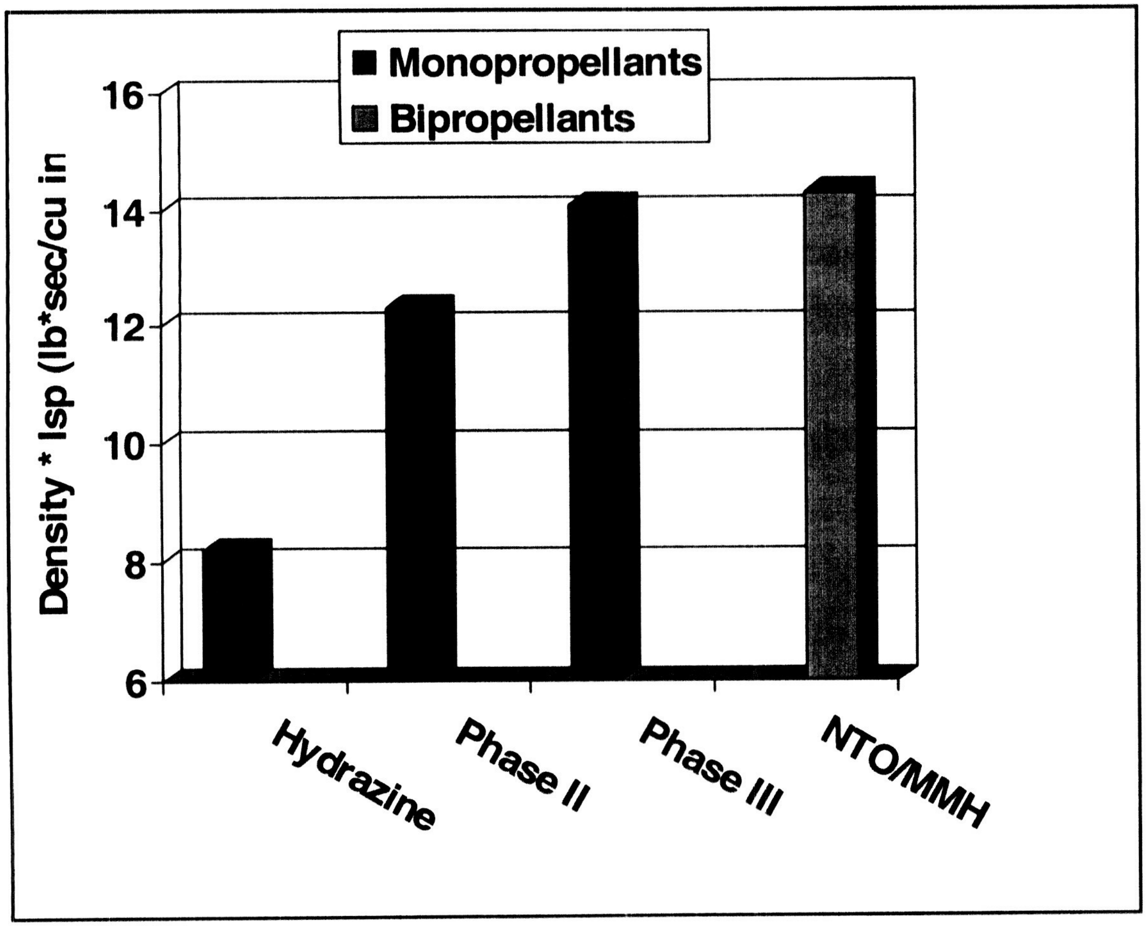


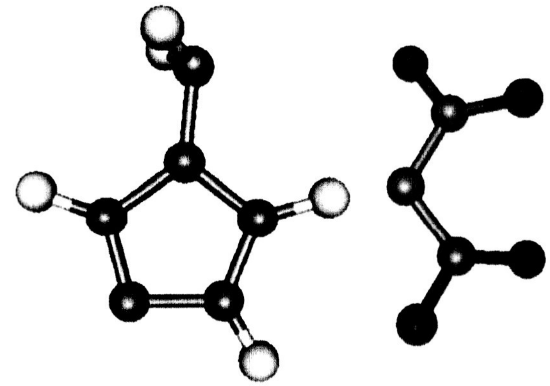
Collaborative Research Environment

- Promotes synergy
- Achieves critical mass of talent
- Unique resources for visiting researchers
- Aids technology transition process to industry
- Keeps research relevant
- Focuses research on NASA's needs

High Energy Density Monoprops

- ✦ **Enable New Missions** – smaller vehicles, more payload, higher ΔV
- ✦ **Reduce Costs** – simpler, smaller, lower-cost propulsion system





4ATDN

Several mono-props have been formulated that substantially outperform hydrazine and even surpass bi-props for some applications

Hypergolic Ignition of H_2O_2 and

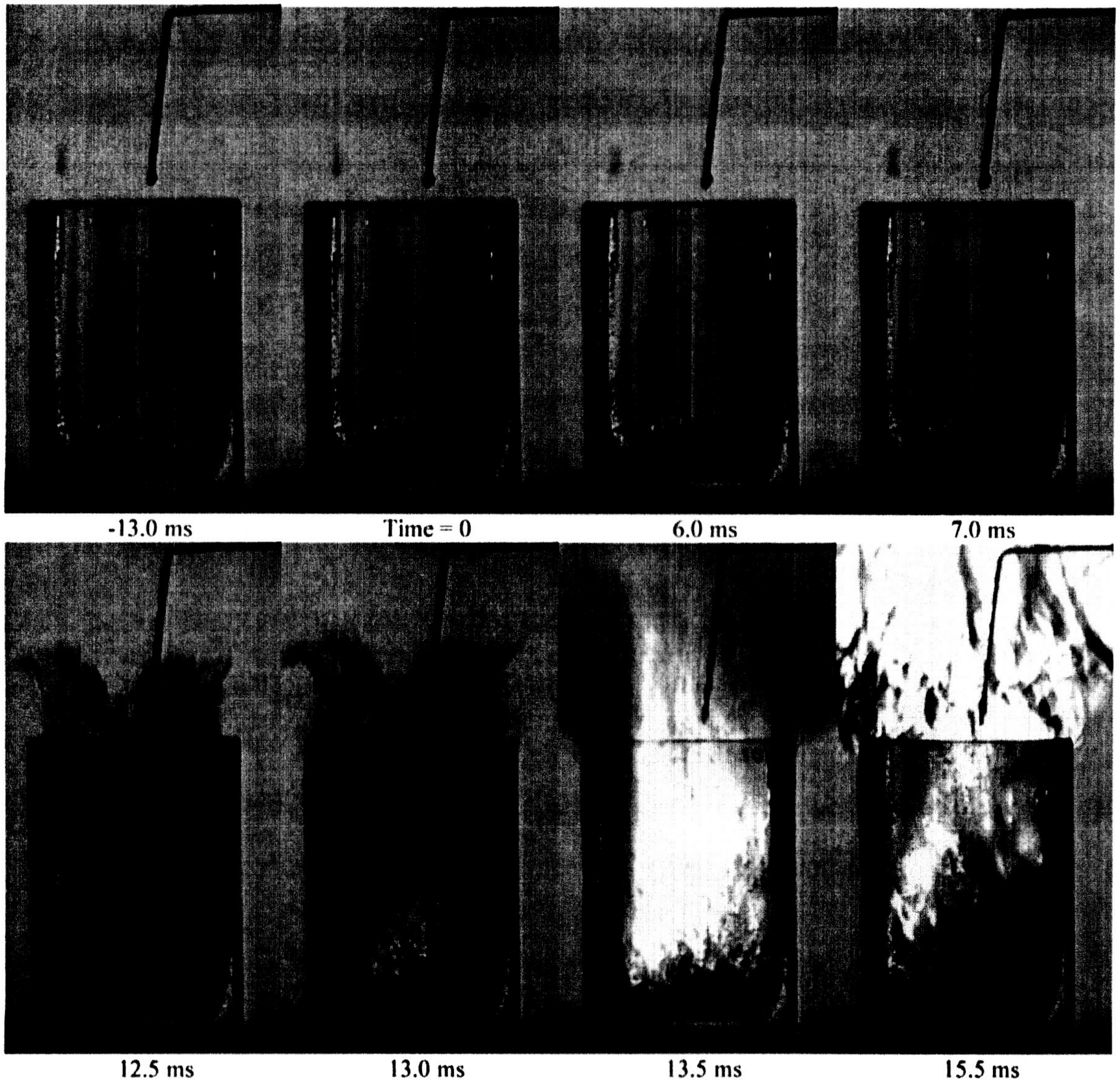
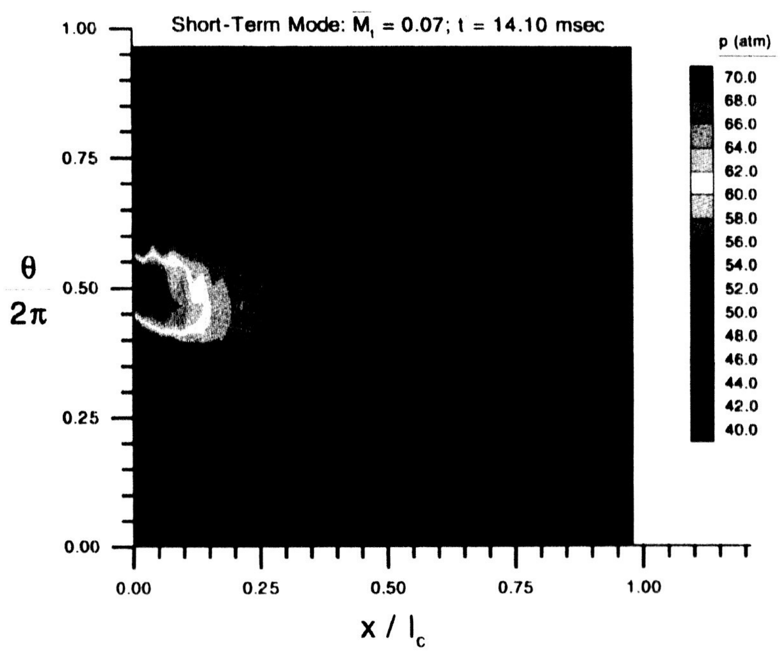


Figure 4. Series of Drop Test Schlieren Images N,N-Dimethylhexylamine Based Fuel Mixture

- Optimize fuel blends for reaction with hydrogen peroxide
- Desire reaction kinetics sufficiently fast to avoid engine "hard starts"
- Demonstrated $\approx$ 10 msec ignition delays with 98% H_2O_2
- Application Interests
  - high temperature catalyst
  - hypergolic hydrocarbons

Liquid Rocket Combustion Instabil

- **Liquid Rocket Combustion Instability Research**
  - Destructive resonant combustion in liquid rockets continues to be a major risk in the development of new engines
  - Recent theoretical/computational research has shown that injector face vorticity production may play an important role
  - Developing apparatus to examine this hypothesis in a laboratory environment



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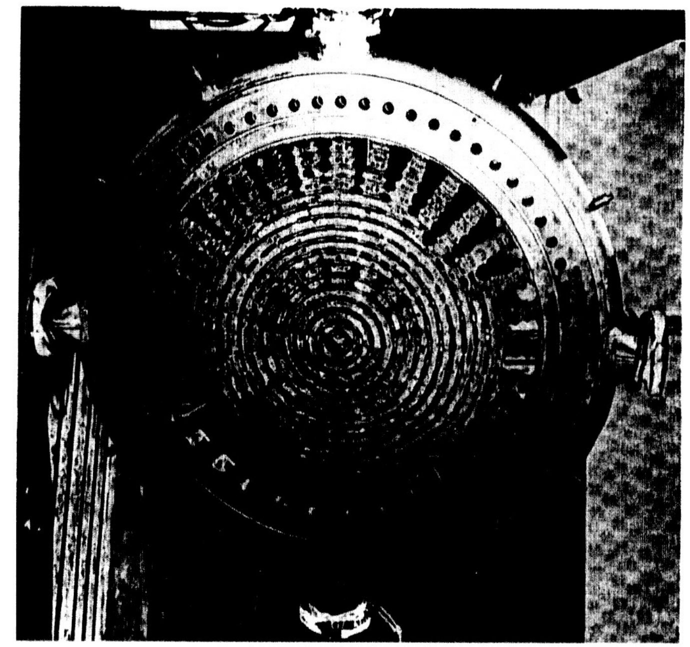
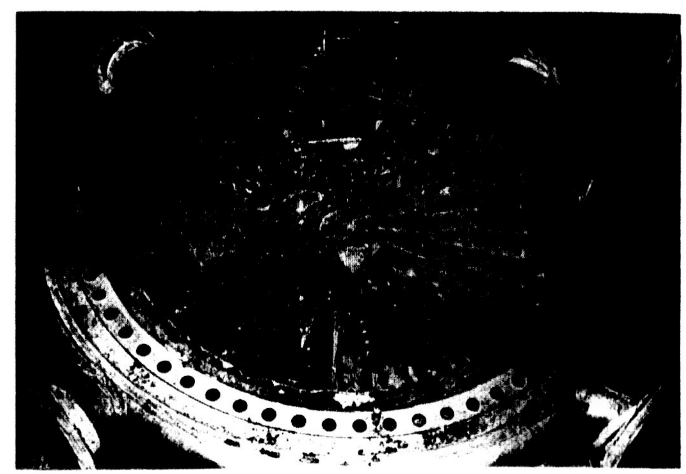




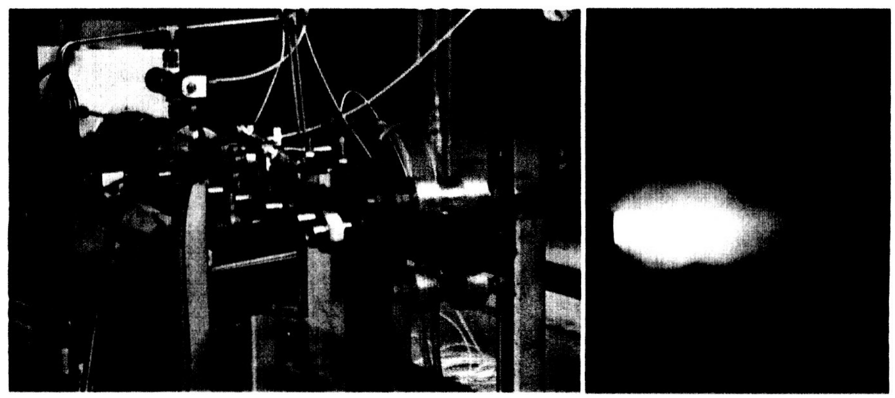
... after

Energetic Combustion Techno

- **Powdered Metal Combustion Technology**
  - Endo-atmospheric Mars propulsion
    - Metals/CO_2 combustion utilizes in-situ resources
    - Ascent stage for Mars sample return mission
  - Thermal driver for pulse power MHD generator
    - Nonequilibrium Plasma Generator (NPG) concept
    - High-power airborne APU
  - Adapt existing experimental device to investigate fundamental combustion processes
    - Pressurized rig with optical access
    - Positive displacement fluidized bed feed system
  - Demonstrate prototypical rocket mode operation

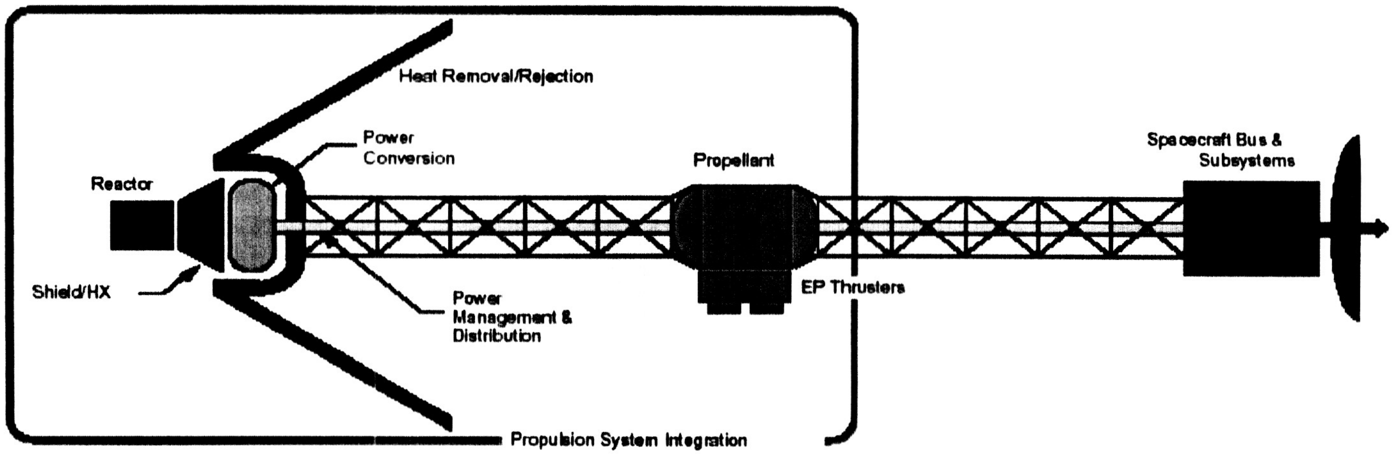
Powdered Metals Research Combustor

- **Pulse Detonation Combustion Technology**
  - Rocket/airbreathing propulsion
  - Impulse bit in-space thruster
  - Thermal driver for pulse power MHD generator
  - Developed and tested gas-fed research engine
    - 2-inch bore with optical access
    - Digitally controlled valves and firing circuitry
  - Evolve to liquid-fed research engine



Pulse Detonation Research Engine

Early Flight Nuclear Electric



- ✦ Nuclear electric propulsion can significantly enhance deep space science missions
  - Faster missions without need for gravity assist maneuvers
  - Higher payload capability
  - Multiple destinations / longer stay times
  - Power rich bus enhances science experiment capability
  - Enables outer moon tours and outer planer sample return missions
  - Reactor technology adaptable for exploration *surface power* needs
- ✦ Power and specific mass requirements less strenuous
  - Power level $\approx$ 60 to 120 kW_e
  - Specific mass $\leq$ 50 kg/kW_e
  - Good candidate missions for near-term demonstration of nuclear electric flight system

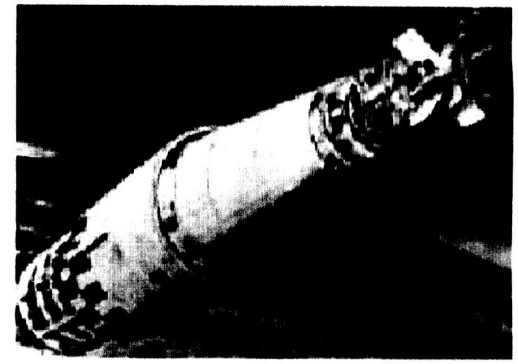
... for example, Jupiter Icy Moons Orbiter (JIMO)

Solid Technical Base for Space

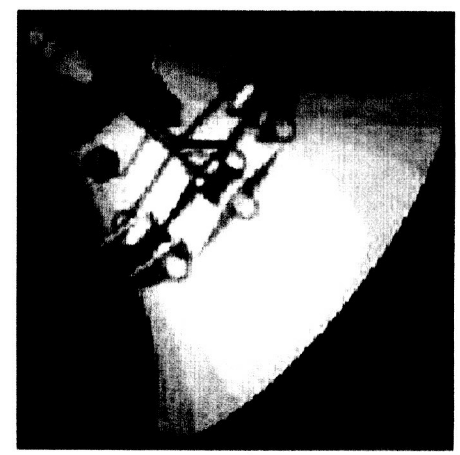
- US SNAP program
  - SNAP-10A launched in 1965
  - Reactor power 0.5 kWe
  - 43 days space operation, 1 yr grd test

- US SP-100 program
  - 40 kWe design complete, 100 kWe design ongoing

- Russian RORSAT, TOPAZ programs
  - 38 reactors launched
  - Reactor power 2-5 kWe
  - 1978 RORSAT crash in Canada



1965 OPS 4682 with SNAP-10A Reactor and Ion Thrusters



SP-100

Boeing 100 kW design

Space Nuclear Reactor Options

Heat Transport From Reactor
- Heat Pipe
- Pumped Liquid Metal
- Direct Gas Cooled

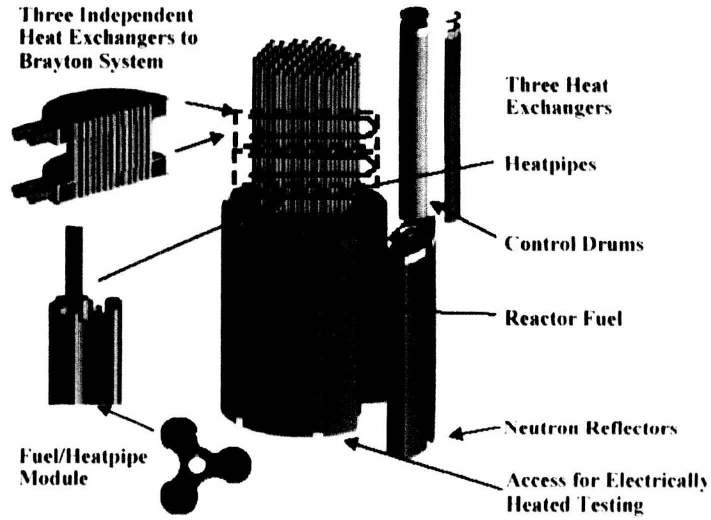
Power Conversion
- Brayton
- Stirling
- Rankine

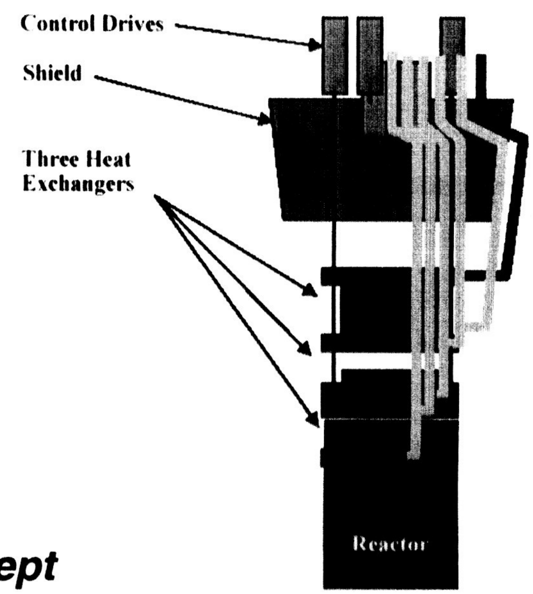
  } η= 20% – 30% reliability issues
- Thermoelectric
- Thermionic

  } η = 4% – 14% high reliability

Heat Rejection
- Pumped Loop
- Heat Pipes

PMAD
- AC or DC
- Low or High Voltage

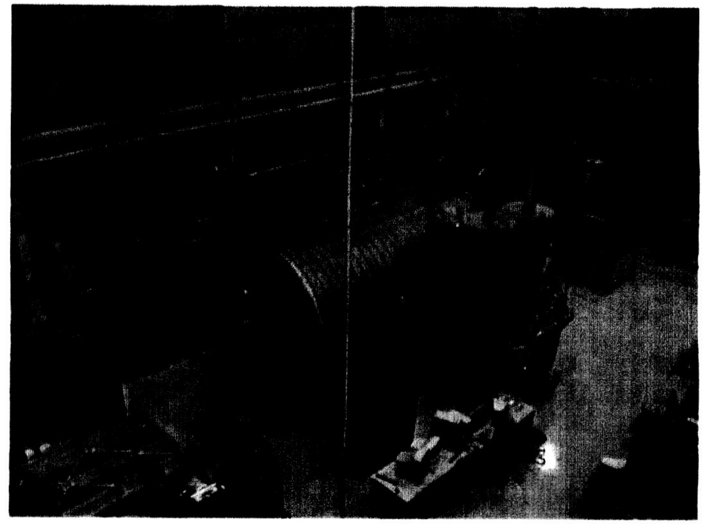




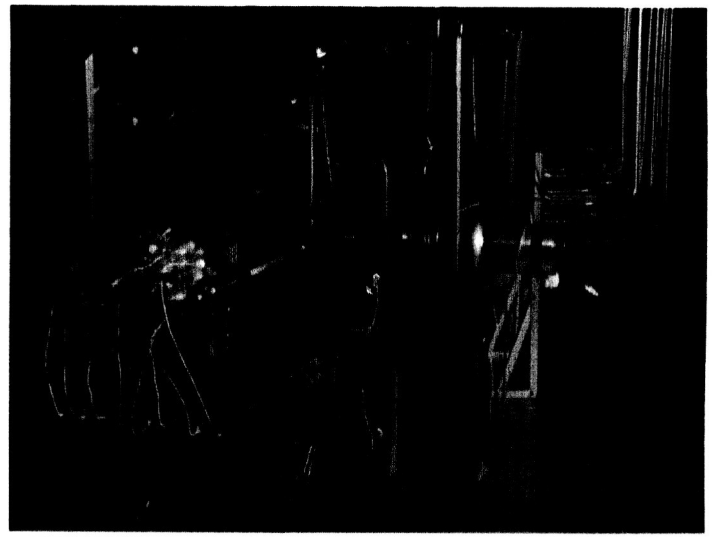
Heat Pipe Reactor Concept

Simulated Reactor Development

- Non-nuclear reactor simulation capability
  - **Facilitate reactor development and system integration**
  - **Focused on cooperative efforts with DOE, industry, universities, and other NASA centers**
  - **Low cost demonstration of thermal design integrity and investigation of integrated component and subsystem performance**

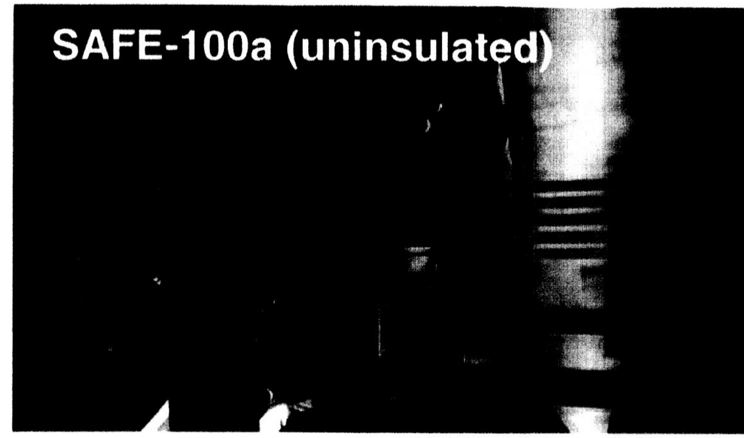


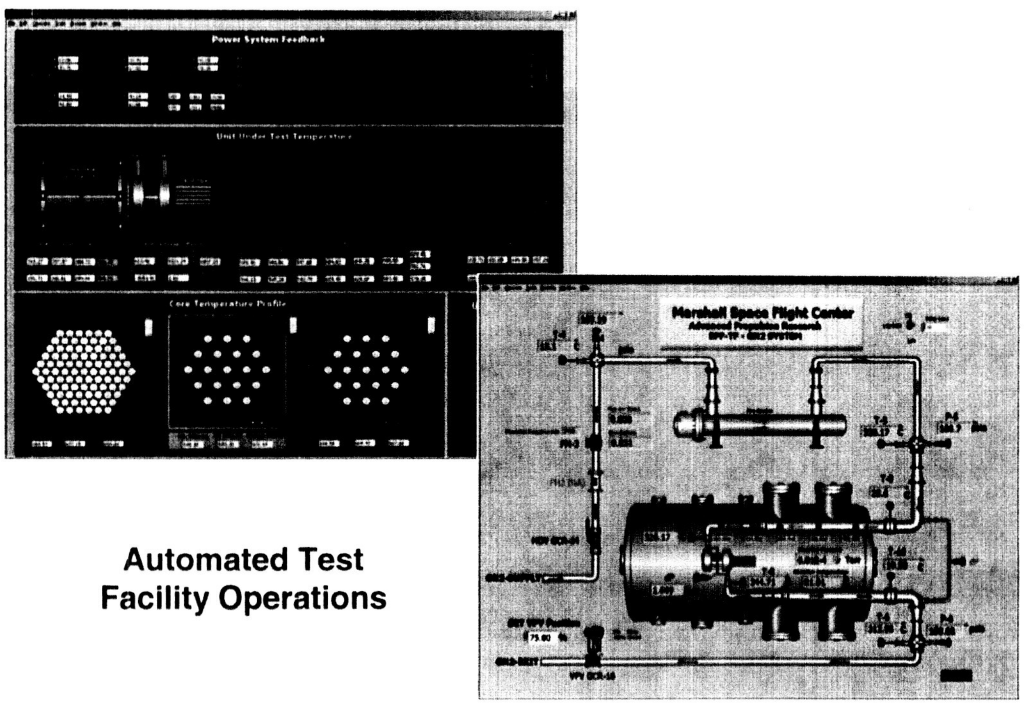
- Safe-30 Systems Demonstration
  - **End-to-End NEP system demonstration of simulated heat pipe reactor with stirling engine power conversion and single ion thruster**
  - **Operation for more than 1 year**
  - **Proved long term reactor core survival under prototypical thermal stress**



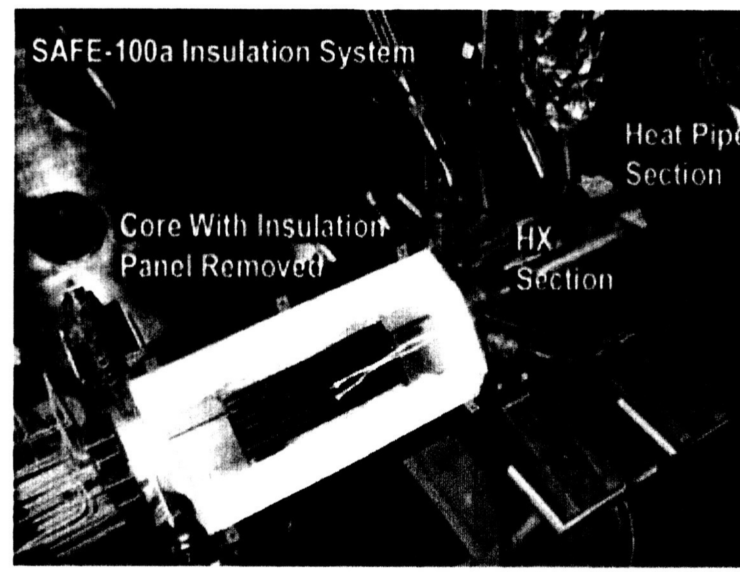
Simulated Reactor System Dem

- SAFE-100a Simulation
  - **Prototypical reactor power level**
  - **Vacuum environment**
  - **Insulated core, HX, HP condensers**
  - **Checkout testing ongoing**
  - **Goal is to demonstrate operation of integrated system**

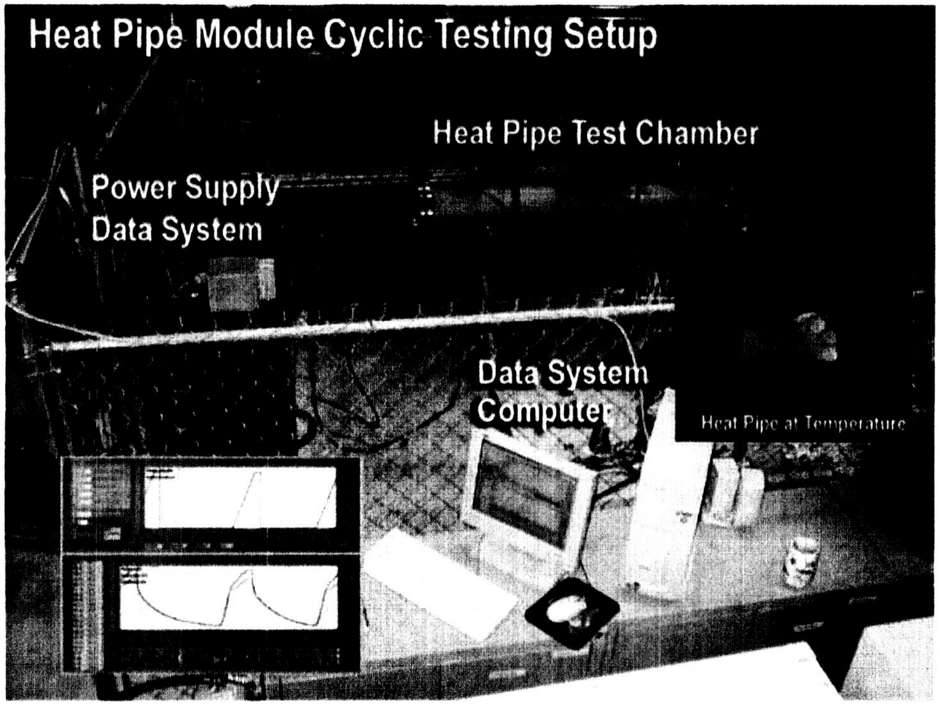




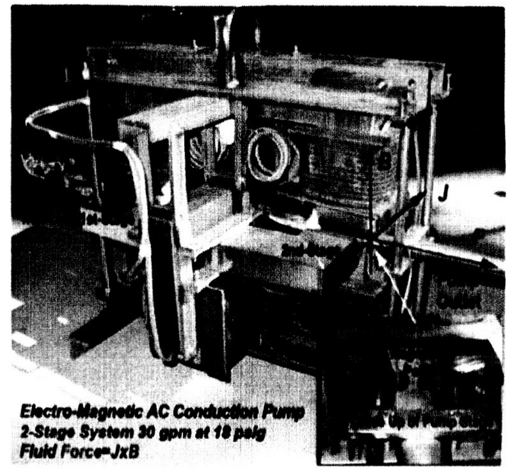
Automated Test Facility Operations



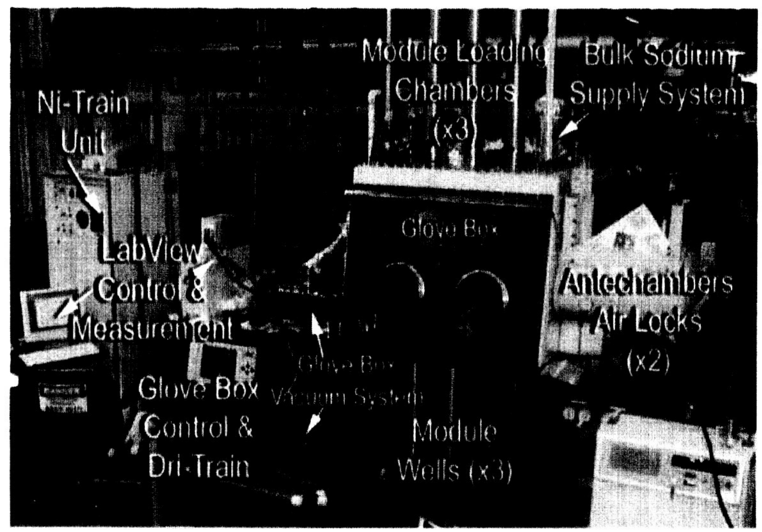
Reactor Component Developm



Demonstrates Multiple Restart (Passive Freeze/Thaw) Capability of Heat Pipe Modules – Established Hardware Test Capability with Fully Automated Control & Data Systems



Liquid Metal EM Pump (1.5 kg/sec NaK-78)



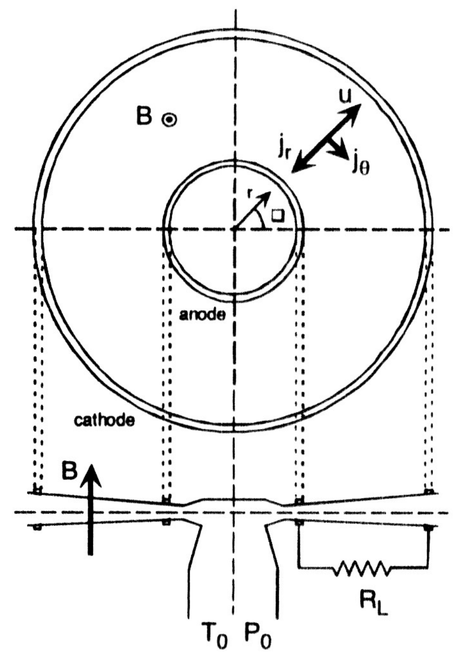
Alkali Metal Purification/Verification System

Evolution to High Specific Power

- **Low power (~100 kW) NEP with static power conversion best near-term prospect for supporting outer planet space science missions**
  - Extensive technology base / low risk
  - Evolvable for future surface power applications
  - But … specific mass characteristics are extremely low ($\alpha \sim 50$ kg/kW$_e$)
- **Nuclear space power with turbo-generator energy conversion is next evolutionary step**
  - Peak cycle temperature constrained by maximum turbine blade temperature limit
  - Operates with low heat rejection temperature ($\alpha_{rad} \propto 1/T^4$)
  - Limited system specific mass ($\alpha \sim 5 - 10$ kg/kW$_e$)
  - No clear development path to obtain $\alpha \leq 1$ kg/kW$_e$

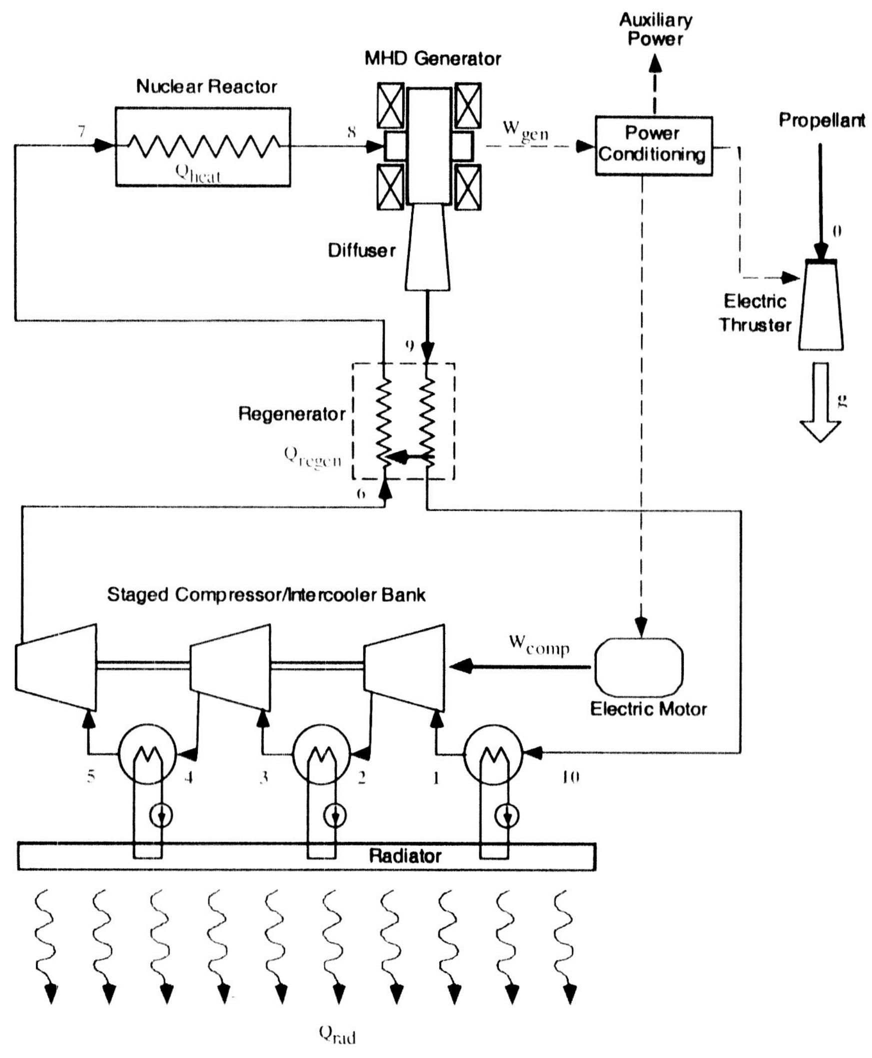
… How can NEP break through 1 kg/kW$_e$ barrier?

- **Closed-Cycle MHD Nuclear Space Power**
  - Lightly stressed channel with no moving parts
  - Heat transfer rate determines thermal limits
  - Ability to extract energy at high temperature
    - solid core reactor (1800 – 2500 K)
    - gas core reactor (8000 – 10,000 K)
  - Non-equilibrium Hall disk generator looks attractive



Hall Disk MHD Generator

CCMHD Nuclear Space Power Sy...



Brayton Cycle vs. Rankine Cycle

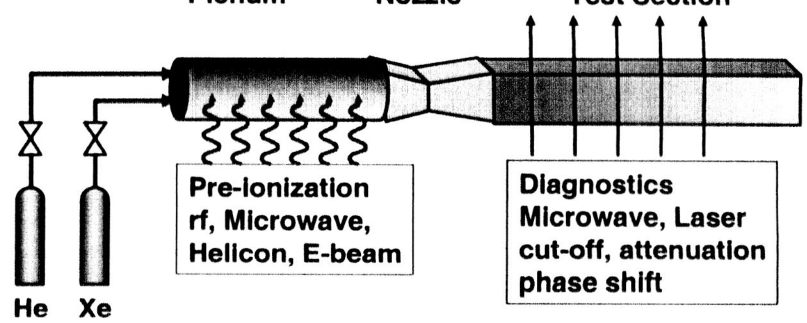
- **Brayton slightly inferior in performance**
- **Avoids highly corrosive condensing vapors (i.e., can utilize inert gas working fluid)**
- **Compatible with solid-core reactors (i.e., leverage NERVA technology base)**

CCMHD Space Power R&D

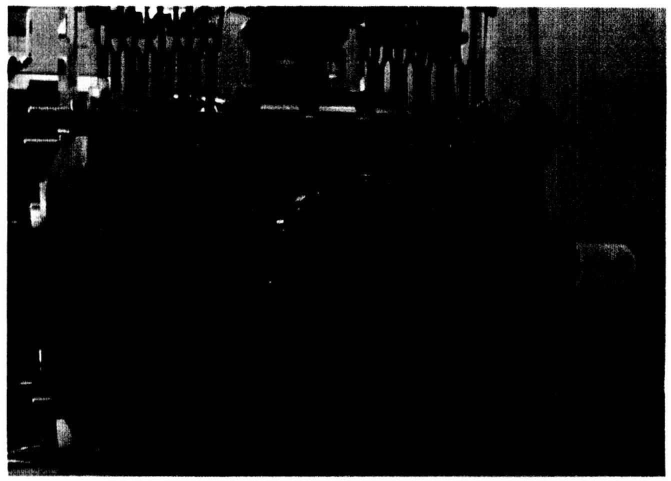
- **MHD In-Space Power Experiment (MIPX)**
  - Investigate CCMHD power using non-corrosive He + Xe mixed inert gas with pre-ionization
  - Resolve critical technical issues and demonstrate the technology
  - Collaborative R&D: NASA-MSFC, Nagaoka University of Technology, LyTec, others?

- **R&D Plan**
  - Phase I: Proof of Principle Experiment
    - Investigate helicon pre-ionization method
    - Power requirements & efficiency
    - Pre-ionization mechanism (Penning effect?)
    - Confirm recombination coefficient
  - Phase II: Power Generation Demonstration
    - He/Xe, T_{max}=1800 K, P_s = 0.2 MPa, B = 3 T
    - 1.5-MW arc-heater / 3-T SC Helmholz magnet
    - Preliminary design completed by Nagaoka University of Technology
  - Phase III: Closed Loop System Demonstration
    - Simulated nuclear reactor source
    - Prototypical scale

Phase I Proof of Principle Experiment

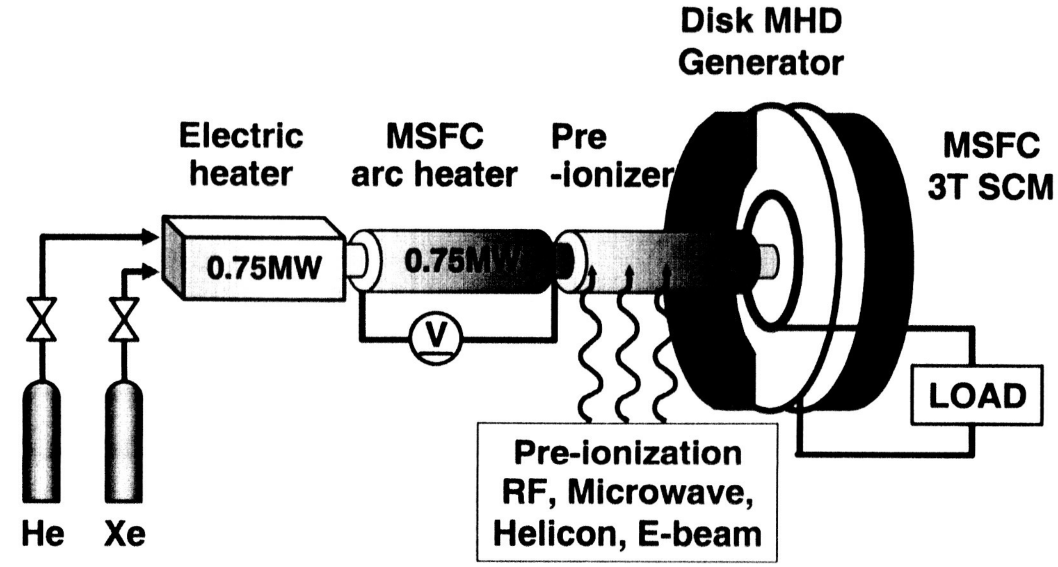


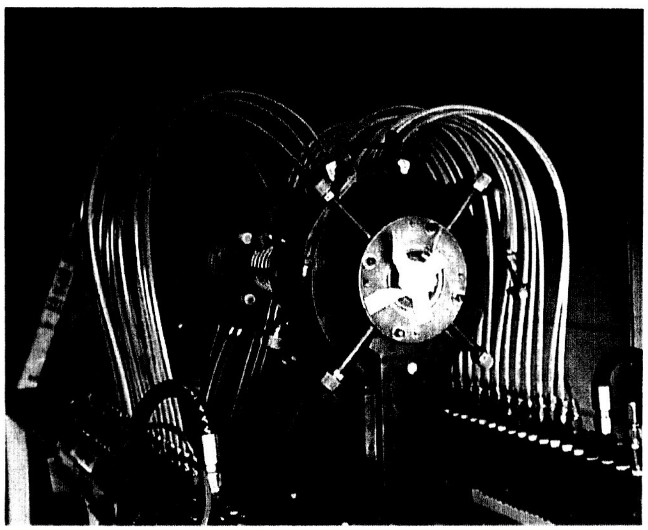
Diagnostic Measurements
- Electron Number Density (MW Interferometer)
- Electron Temperature (Langmuir probe)
- Ion Velocity/Temperature (LIF)



NASA-MSFC 4-KW Helicon Plasma Source

Phase II CCMHD Power Generation





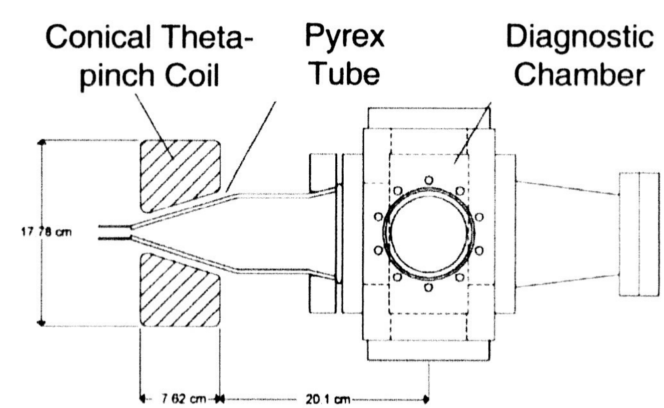
NASA-MSFC Multi-Gas Arc-Heater

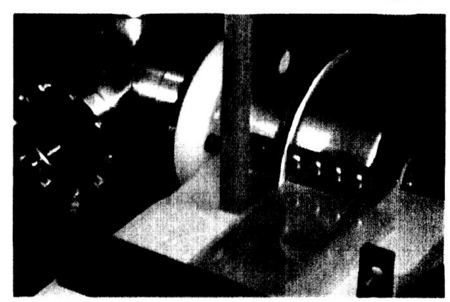
NASA-MSFC 3-Tesla SC Helmholz Magnet

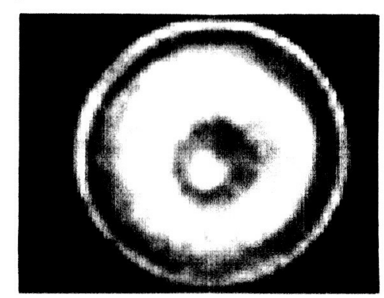
High-Power Plasma Thruster D...

- **Gallium Electromagnetic Thruster (GEM)**
  - Two-stage pulsed plasma thruster that avoids gas valves and high current switches and mitigates electrode erosion
  - Performance characteristics
    - 100 – 500 kW power level
    - 7500 sec specific impulse
    - > 50% efficiency

- **Plasmoid Thruster**
  - An inductive pulsed plasma thruster that repetitively forms and accelerates a compact toroidal (magnetized) plasmoid
  - Performance characteristics
    - 100 kW – 1 MW power level
    - 5000 – 10,000 sec specific impulse
    - > 50% efficiency



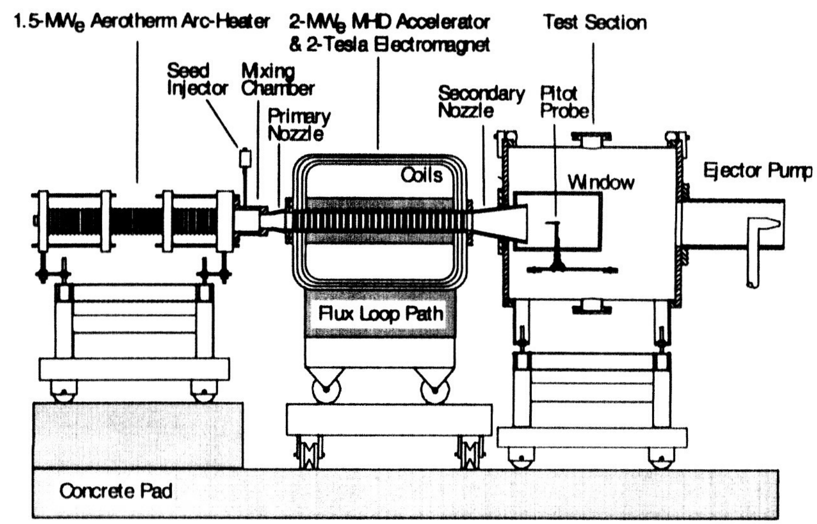




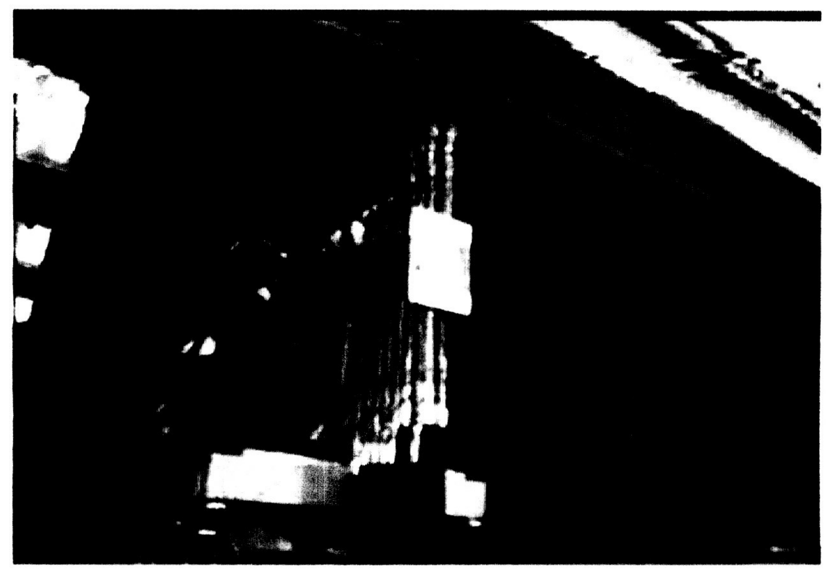
High Power Plasma Thruster D...

- **MHD Augmented Propulsion Experiment (MAPX)**
  - Electrical augmentation of thermal rockets
    - > 1 MW power level
    - 1000 – 3000 sec specific impulse
    - > 60% efficiency
    - Improved capability for high payload missions
    - Hybrid thermal-electric approach increases reliability and improves mission reliability

    "Assured Propulsion Capability"
  - Hypersonic Aerodynamic Test Facility



- **MAPX Description**



Nuclear Thermal Rocket Propul

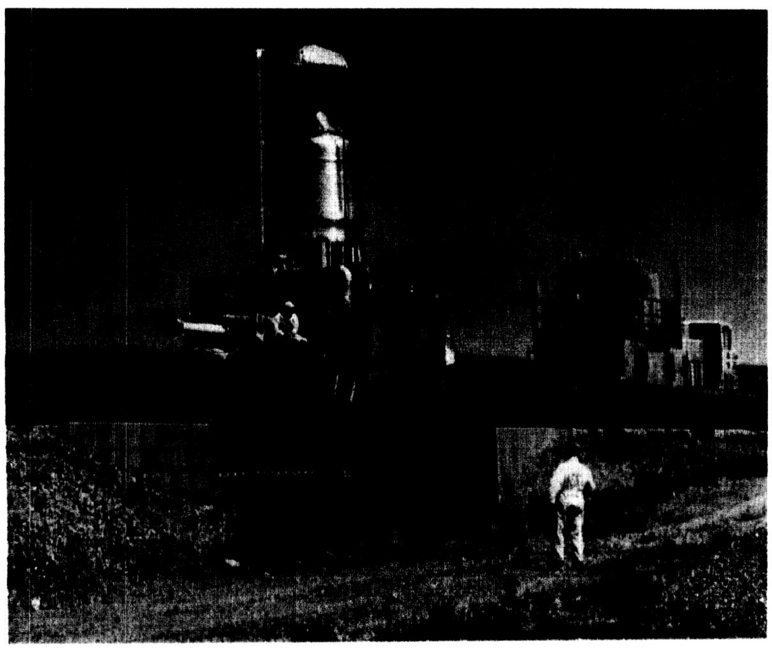
- **Renewed interest in nuclear thermal propulsion to support exploration vision**
  - High thrust with moderately high Isp
  - Combination of high temperature and low molecular weight $\Rightarrow$ potential Isp $\approx$ 900 – 1000 sec
  - Dramatically shortens Mars missions (12-14 months versus 2-3 years using chemical propulsion)
  - Short operation times (2 – 3 hours) to achieve desired $\Delta V \Rightarrow$ reduces reliability risks

- **Engine performance governed by maximum fuel element temperature**

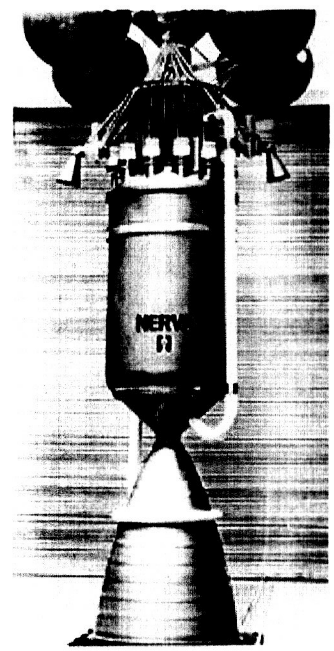
- **Reactor endurance/reliability is very sensitive to fuel element operating temperature**

Technical Base for Nuclear

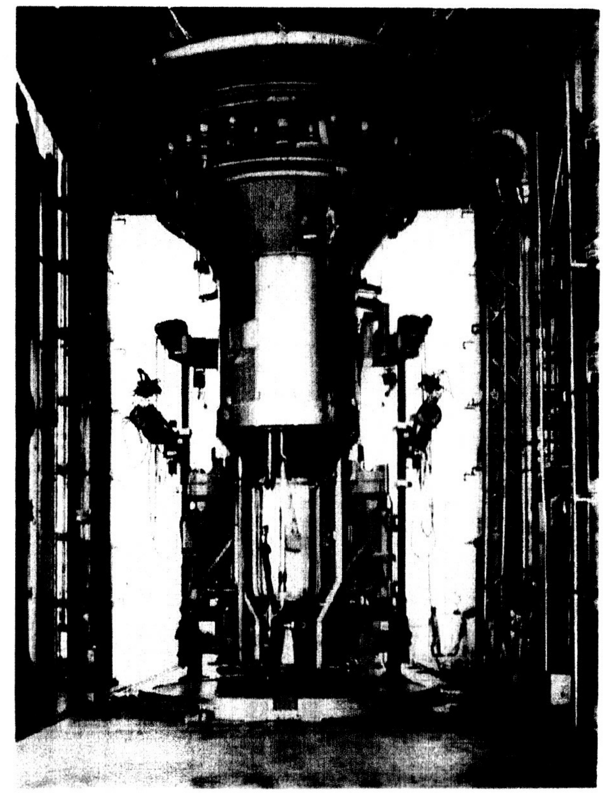
- **U.S. Rover/NERVA Program (1955 – 1973)**
  - Fundamental Reactor Tests (Los Alamos National Laboratory)
    - Kiwi-A, Kiwi-B, Phoebus, Pewee, and the Nuclear Furnace
  - Engine Systems Tests (Aerojet/Westinghouse Team)
    - NRX/EST and XE-Prime
- **Soviet Program (1970 – 1986)**



Phoebus-2A
- Tested 1968
- 5-GW Reactor Core
- 805-sec Isp
- 250,000-lbf Thrust



NERVA (NRX/EST)
- Tested 1966
- 1.57-GW Reactor Core
- 825-sec Isp
- 75,000-lbf Thrust



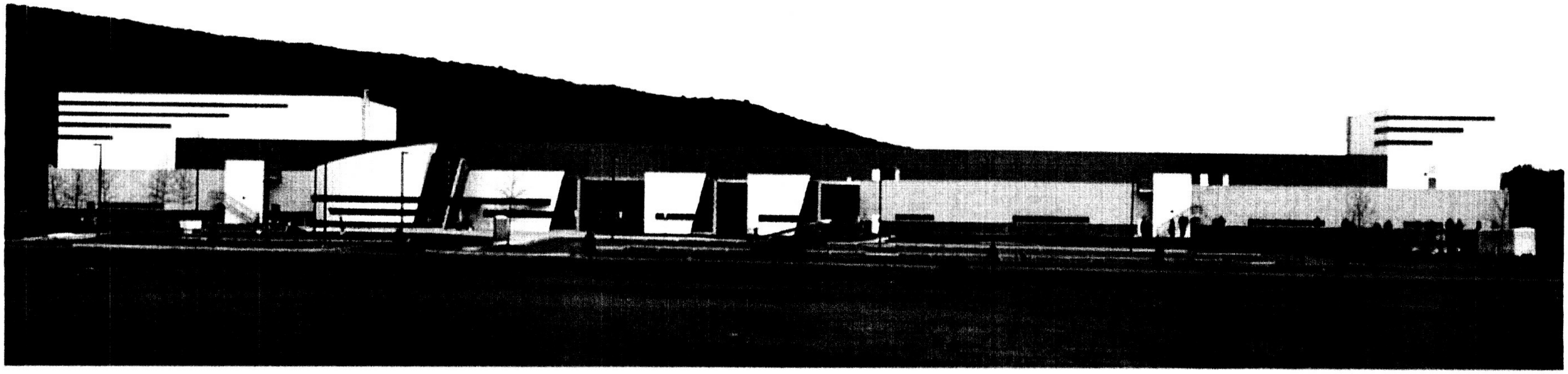
XE-Prime Engine
- Tested 1969
- 1.1-GW Reactor Core
- 820-sec Isp
- 55,000-lbf Thrust

Nuclear Thermal Rocket Resea

- **Reactor Core Durability**
  - Severe fuel element degradation at high T
    - GH_2 takes on aggressive scouring action
    - Erodes/cracks/corrodes protective coatings
    - 10-fold increase in mass loss rate for every 200 K increase in temperature
    - Mass loss limits life & perturbs core neutronics
    - GH_2 penetrates and weakens fuel-matrix structure
  - High mechanical stresses
    - Radial pressure drops (channel-to-channel) severely vibrate core modules

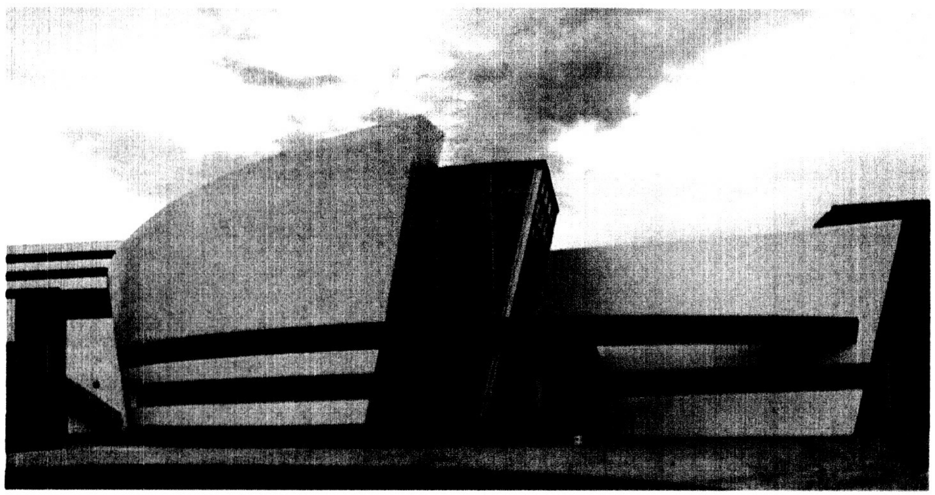
- **Thermal-Hydraulics**
  - Heat transfer correlations not experimentally verified for cooling channel heat flux levels
  - Even though Re, Pr, L/D parameters within stated range of existing correlations, T_w/T_{bulk} ratio exceeds range of database for high heat flux conditions
  - NERVA reports indicate that maximum fuel element corrosion occurred in the mid-band region of the coolant channel
    - Location of maximum temperature gradients, maximum neutron flux, and maximum thermal stresses

Propulsion Research Laboratory

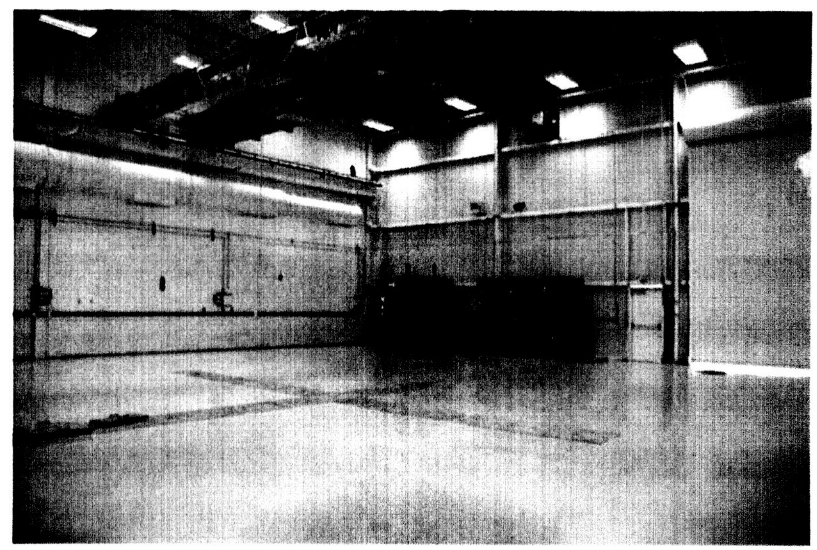


- **Building construction complete**
  - 67,000 ft^2 of useable laboratory space
  - 32 laboratory rooms of various size
- **In process of moving-in and connecting special test equipment**
- **Official ribbon cutting was 29 July 2004**

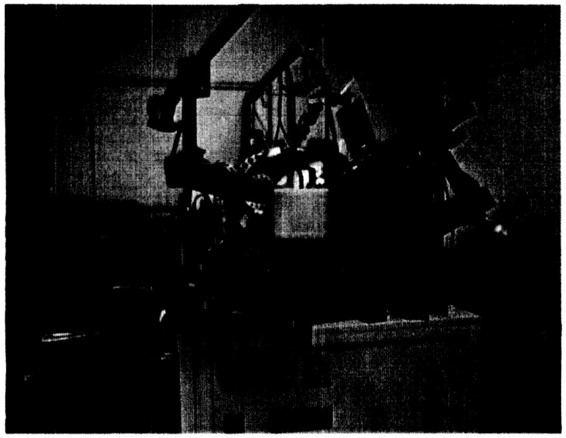
PRL Capabilities



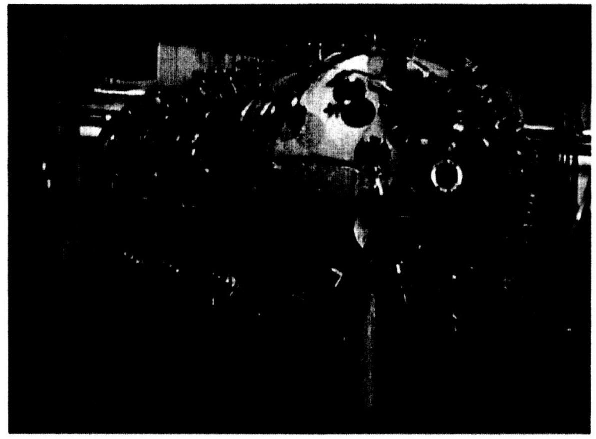
- 10 MW_e total building power
- High purity air & nitrogen connections
- 600 gpm process cooling water
- 5 – 15 ton bridge cranes
- Isolated transformers
- 500-kW backup diesel generator
- Security/key card entry for each lab



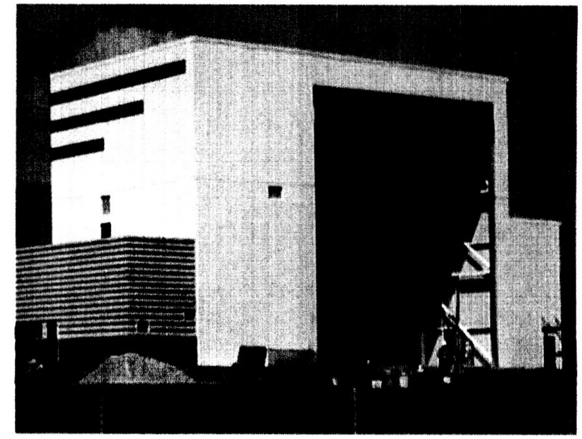
Special Capabilities



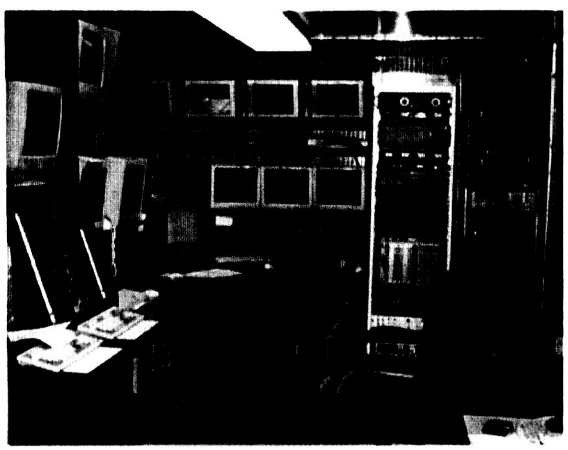
Non-Intrusive Diagnostics



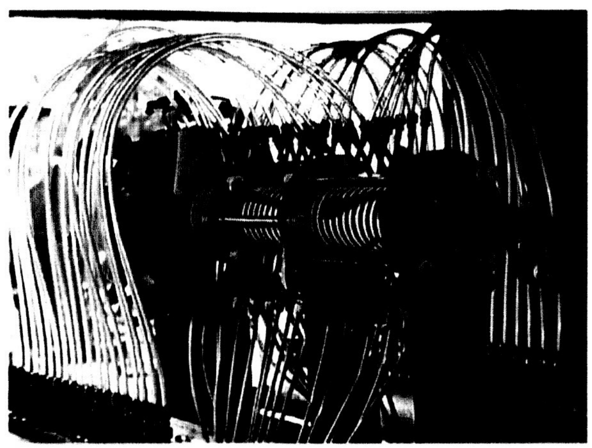
2-12' Diameter Vacuum Chambers



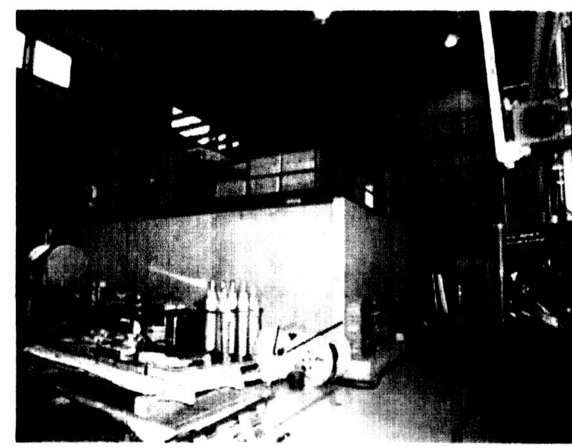
High-Bay for Inflatables Development



High Speed DAQ/Controls

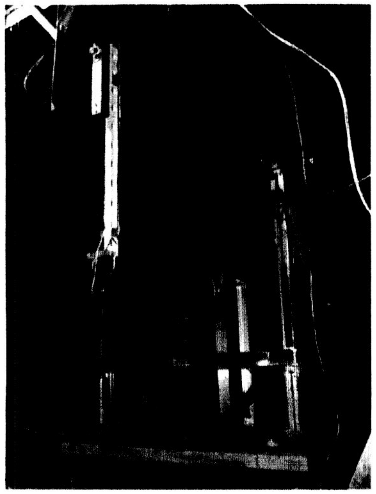


1-MW Arc Heater

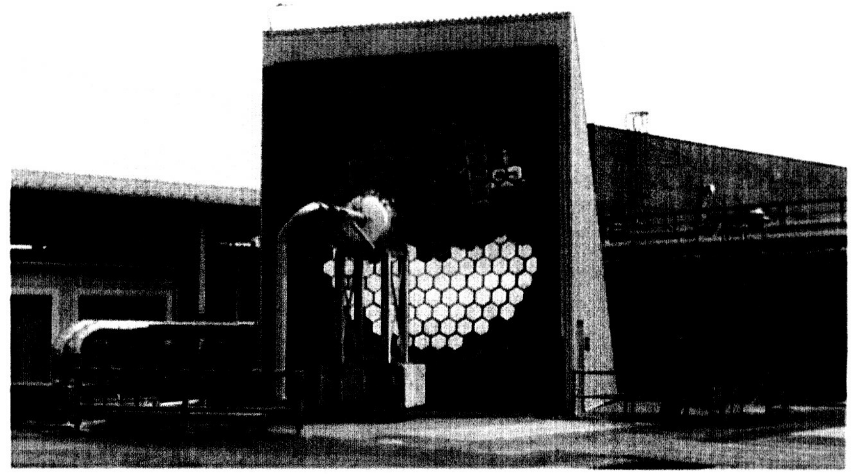


Pulse Power Infrastructure

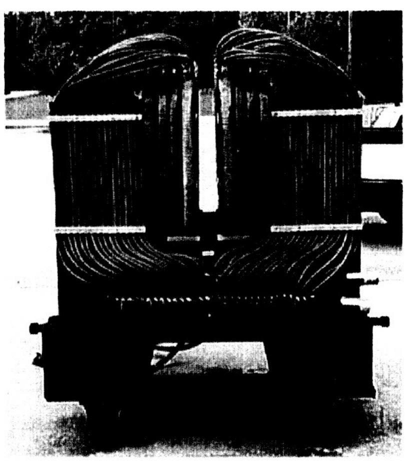
Special Capabilities



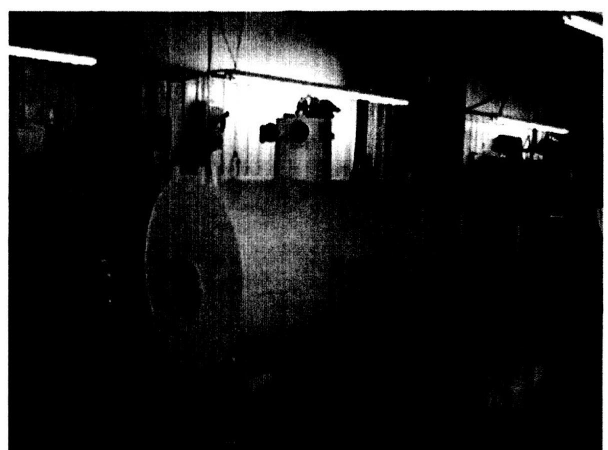
Electric Propulsion Thrust Stand



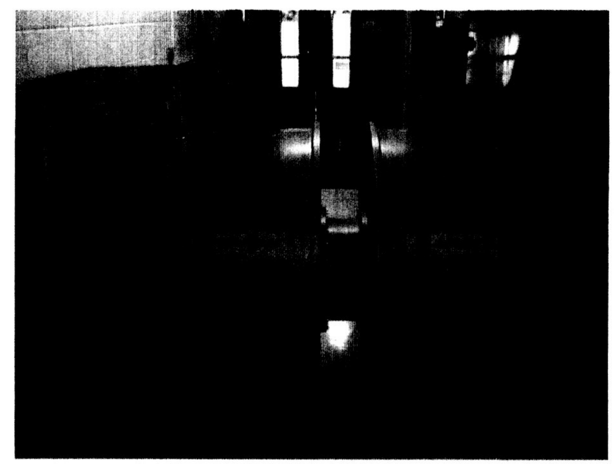
Solar Thermal Furnace



2-Tesla Race-Track
MHD Magnet



6-Tesla Superconducting
Solenoid Magnet



3-Tesla Superconducting
Helmholz Magnet